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BAROTROPIC HURRICANE TRACK FORECAST MODEL

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ABSTRACT

The SANBAR barotropic hurricane forecast track model is applied to the four named Atlantic tropical vortices from 8 September to 13 September 1971. All segments of the program, one of the three major objective tools used at the National Hurricane Center during 1971, are described. The data base includes NHC's history tape plus subjective use of film strips from the ATS III satellite.

SANBAR forecasts are plotted and compared with subsequent storm or hurricane movements. The effects of storm parameter variation are discussed along with an NHC modification to SANBAR promising improved results.

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INTRODUCTION

Since the decade of the fifties, attempts have been made to provide hurricane forecasters with a viable objective hurricane track forecast. During the 1971 hurricane season, the National Hurricane Center (NHC) had three primary objective forecast tools from which to draw before releasing its official advisories on tropical storm and hurricane movements. The first, called NHC-67, is a statistical method developed by Miller et al (1968) which uses a multiple screening regression technique dependent, now, upon prognostic and analyzed values of pressure-height data as well as past storm motion and other synoptic parameters. The second, known as HURRAN (for hurricane analog) produced by Hope and Neumann (1970) selects tracks of similar hurricanes dating back as far as 1886 for possible application to the existing tropical storm or hurricane. The third method, a dynamic one called SANBAR (for Sanders barotropic), developed by Professor Frederick Sanders of the Massachusetts Institute of Technology is the subject of this work. This model is based upon the hypothesis that the advection of mean tropospheric vorticity in the air column containing the storm primarily governs the motion of the cyclone. The depth of the appropriate air column is taken to be from 1000 to 100 mb.

Following attempts using vortex separation (Kasahara, 1957), the technique of barotropic calculation without separation of the storm

vortex from the basic flow has been investigated by Sanders (1959), Birchfield (1960, 1961), King (1966), Ahn (1967), as well as Sanders and Burpee (1968). Next came the substitution of the previous manual analysis with an automated analysis scheme (Sanders, 1968, 1970). The current report investigates the results of SANBAR applied to the several cyclones existing in the tropical Atlantic during the period September 8-13, 1971. An effort is made to improve the wind data available from the NHC history tape, and use is made of satellite information in regions where soundings are unavailable. Additionally, storm parameters are varied to display the effects of such variations upon the forecast tracks.

DATA PREPARATION

Since previous investigations of King (1966) and Ahn (1967) indicate that the 10 mandatory levels represent an optimum vertical sample from which to work, the average wind for each reporting station is approximated by the trapezoidal rule:

$$\overline{\underset{\sim}{V}} = \frac{1}{900}\left[\sum_{i=1}^{8}\frac{(p_{i-1}-p_{i+1})}{2}\underset{\sim}{V}_i + \frac{p_0-p_1}{2}\underset{\sim}{V}_0 + \frac{p_8-p_9}{2}\underset{\sim}{V}_9\right]$$

where: p_o = 1000mb, p_1 = 850mb, . . .p_9 = 100mb

$\underset{\sim}{V}_i$ = the horizontal wind vector for the level specified

(This and all subsequent computations were performed on the IBM 370 Model 155 Computer at the Information Processing Center of M.I.T.)

Winds for the 10 mandatory levels were obtained from magnetic history tapes made available by NHC. For the sample period chosen (0000Z September 6, 1971 through 1200Z September 13, 1971) the number of soundings available at a specific synoptic time ranged from 126 to 146 within the area of the grid -- to be described later. To improve the data base so supplied by the tape, teletype reports were scanned, and missing soundings added when found. When interior level winds were missing, they were interpolated from surrounding levels; winds missing from the bottom or the top were computed by

extrapolation of the lowest or highest level wind available. Finally, those soundings having fewer than two reported winds from the lower 4 levels or fewer than two from the upper 6 levels were rejected and thus considered to be missing. Using this convention on the 16 synoptic times involved, the number of acceptable soundings then ranged from 100 to 122. It may be of interest to note that the number of soundings usable south of 30°N was limited, having a median of 24 while ranging from 22 to 27.

OBJECTIVE ANALYSIS

A. Development Program

After the observed mean winds are prepared, the SANBAR forecast entails the execution of 3 computer programs. The first, called the "development" program may be executed far in advance of the 2 operational programs.

The development program, written by Mr. Peter P. Chase of the National Hurricane Research Laboratory following the procedures proposed by Eddy (1967), provides regression equations which will be used to compute winds for missing stations as well as winds for all 2655 grid points. The numerical grid consists of a 45 x 59 array of grid points extending from the equator to 55°N Latitude and from 36.5°W to 123.5°W Longitude on a Mercator projection true at 22.5°N. The mesh length is 154 km (at 22.5°N). Fundamentally, this program is based on an estimate of the correlation of the observations, or more specifically the observed departures of zonal and meridional wind components from their respective latitudinal means, as a function of distance between observing points. Figure 1 shows this estimated correlation based upon the 1713 input soundings. However, stations within the influence radius of cyclones are excluded from the computation, as are stations having wind greater than 5 standard deviations from the mean of the specific synoptic time period or from the latitudinal mean. (Stations having wind greater than 3 standard

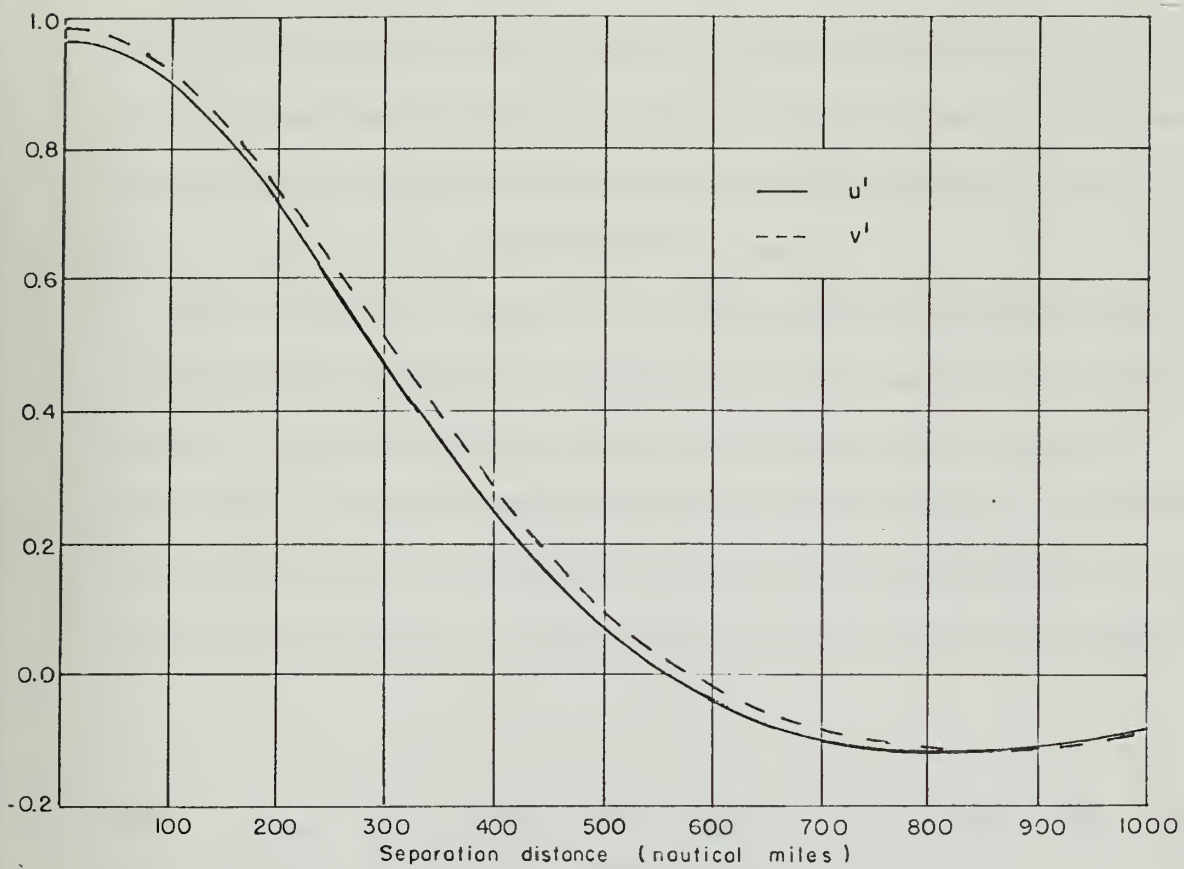

Fig. 1 -- Correlation as a function of separation distance for departures of vertically averaged wind from zonal average values

deviations from these means are "flagged" to permit investigation by operating personnel.) Contrasted with a previous sample of soundings which computed the correlation dropping to zero at 700-800 nautical miles (Sanders, 1970), in the current sample the correlation drops to zero at 560-580 nm. This would seem to imply that within the one week period of this sample, the prevailing size of the circulation was smaller than that of the previous study -- the previous sample

in particular did consist of data from several hurricane seasons. The current sample also displays higher correlation between stations less than 175 nm apart and lower correlation for stations greater than 175 nm apart than did the previous sample.

Table 1 presents a sample of the regression equations generated by the development program -- equations that are used in the following "operations" program should a station be missing during a specific synoptic time. Several stations existing outside the grid are included with the data since they may be used in the regression equations (i.e., they are within 580 nm). Similar regression equations are generated

DESIRED STATION	LAT.	LONG.	INPUT STA.A	COEFFICIENT STA.A	INPUT STA.B	COEFFICIENT STA.B	INPUT STA.C	COEFFICIENT STA.C	INPUT STA.D	COEFFICIENT STA.D
(72201)	24.5	-81.8	(72202)	1.23389E 00	(78063)	-4.43094E-01	(78384)	1.71994E-01		
U.V UNEXP	0.125	0.081	(72202)	1.34541E 00	(78063)	-5.40235E-01	(78384)	1.59612E-01		
(72202)	25.8	-80.3	(72201)	5.42278E-01	(78063)	5.20942E-01				
U.V UNEXP	0.061	0.038	(72201)	5.44171E-01	(78063)	5.22169E-01				
(72206)	30.4	-81.6	(72213)	6.94288E-01	(74794)	3.36854E-01				
U.V UNEXP	0.055	0.033	(72213)	7.04969E-01	(74794)	3.30769E-01				
(72208)	32.9	-80.0	(72213)	8.05680E-01	(72317)	2.74069E-01	(72221)	-2.45112E-01	(72304)	2.16437E-01
U.V UNEXP	0.102	0.069	(72213)	7.35277E-01	(72317)	6.51539E-01	(72221)	-2.24192E-01	(72425)	-2.55959E-01
(72211)	28.0	-82.5	(74794)	8.03003E-01	(72221)	2.28216E-01	(72201)	3.34919E-01	(78063)	-2.53290E-01
U.V UNEXP	0.086	0.055	(74794)	6.39378E-01	(72221)	2.15591E-01	(72201)	3.43492E-01	(78063)	-2.92064E-01

Table 1. Regression equation coefficients for computing winds for missing stations. (Winds are computed for the station in the left-most column using wind components of stations to the right with the associated coefficients -- zonal component on top row, meridional component on bottom row. Unexplained variance for both the u and v components are shown also.)

to provide winds at each grid point -- winds which are subsequently used in forecast calculations.

Required as input to the development program are:

1. A station list supplying block and index numbers as well as latitude and longitude (the 185 northern hemisphere stations in this investigation included several now defunct stations should SANBAR be tested on storms from recent previous years);

2. Mean winds from available soundings (in this study, 1713 soundings for the 16 synoptic time periods during the sample period chosen);

3. The tropical storm and hurricane data for each synoptic time period (latitude, longitude, and maximum influence distance).

In deriving the correlation curve and regression equations, the statistics of the wind data are assumed to be isotropic (aside from the latitudinal trend), homogeneous, and stationary. As noted by Sanders (1968), the failure of the data to meet these requirements does not appear to lead to crucial errors in the final analysis. We have noted in particular an instance of non-stationarity in the comparison of samples discussed above. Nevertheless, this is not meant to imply that continued research in this area is not welcomed.

B. Operations Program

The operations program, also written by Mr. Chase, must be executed each time in preparation for the barotropic forecast. Its ultimate purpose is to provide u and v wind components for each grid point in

the array. Required as input to the program are:

1. Mean winds for soundings at the specific synoptic time for which a forecast is desired (Additional estimated mean winds must be provided for data-sparse regions, as described below.);

2. Hurricane parameters for the specific synoptic time (latitude, longitude, maximum influence distance, maximum surface wind, and eye diameter -- the maximum influence distance is subjectively estimated from the surface analysis).

Mean winds from soundings are supplemented by "bogus" winds for the 44 locations indicated over data sparse and oceanic regions shown in Figure 2. Below 35°N, the first estimate of the mean wind at bogus points was made from 200 mb and surface analyses prepared by NHC. Assuming a linear variation of the wind from the surface to 100 mb, the contributions of the 200 mb and of the surface winds are .56 and .44 respectively. However, comparison of mean winds already computed during the data preparation for certain oceanic stations, such as Bermuda, often indicated that weighting factors should be near .30 and .70 respectively -- i.e., a heavier weight given to the surface wind than to the 200 mb wind. Accordingly the weight given the 200 mb wind and the surface wind was subjectively determined. A great assist in preparing the bogus winds for 0000Z, came from viewing film strips from the Applications Technology Satellite III (ATS III).

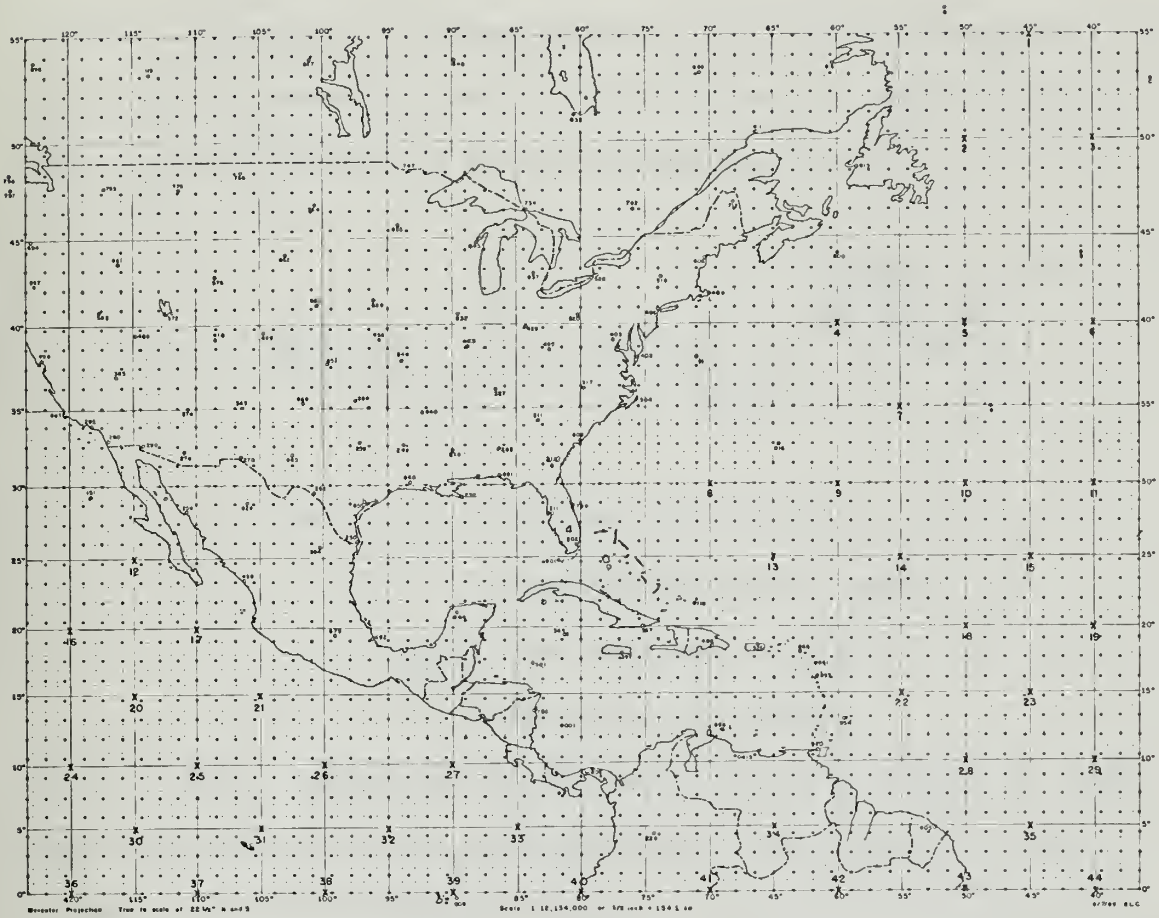

Fig. 2 -- SANBAR Numerical Grid (X's indicate the forty-four bogus points.)

Above 35°N it is found that the geostrophic wind measured from the 500 mb analysis provides a very close estimate of the mean wind.

Immediately after reading in the station and bogus data, the input parameters for any storms present are used to identify those winds which are within the maximum influence radius of the storm.

Within this radius, the storm/hurricane circulation is subtracted from the observed mean winds leaving a "recalculated" or storm-purged wind. This model hurricane wind determined empirically as

$$V = 0.72\, V_{max} \left[\sin \pi \left(\frac{R}{R_{max}} \right)^{\frac{\log 0.5}{\log E/R_{max}}} \right]^{1.5}$$

where: V_{max} = Maximum surface wind

R = Distance from storm center

R_{max} = Max. influence distance

E = Hurricane eye diameter

is vectorially subtracted from the input wind in an attempt to depict what the undisturbed wind would have been. Then anomalous winds are rejected as in the development program. If winds from stations used in grid-point regression equations are missing, they are reconstructed using station regression equations from the development program. However, should this be impossible because of additional missing data, ad hoc regression equations are generated from the winds which are present.

The analysis for the entire array is then carried out by solving, at each grid point, the regression equation for the zonal and meridional components of the wind. Finally at those grid points within the influence radius of a storm, the zonal and meridional components of the storm are added to the values estimated from the regression

equations to complete the analysis.

Additional computations are made to show the closeness of fit of the analysis to the data, but they will not be discussed here.

FORECAST MODEL

The Sanders barotropic hurricane forecast track program, written with the programming assistance of Dr. Robert W. Burpee and Mr. Frederick S. Zbar while they were graduate students at M.I.T., has at its beginning a brief section entitled Diagnosis. Using the operations program wind analysis components as input, relative vorticity is computed by a simple centered finite-difference approximation

$$\zeta_{i,j} = \left(v_{i+1,j} - v_{i-1,j} - u_{i,j+1} + u_{i,j-1} + \frac{2\Delta u}{r} \tan\theta \right) \frac{m_j}{2\Delta}$$

where: ζ represents relative vorticity

u represents the eastward wind component

v represents the northward wind component

Δ represents the mesh length

r represents the earth's radius

θ represents latitude

m represents the map factor

i,j represent the x and y grid positions respectively

for all interior grid points, with boundary values set to zero. After smoothing the relative vorticity field, stream function values are obtained by solving the Poisson equation using a 9-point laplacian operator and an extrapolated Liebmann relaxation technique

$$\psi_{i,j}^{\nu+1} = C_1 \psi_{i,j}^{\nu} + C_2 \Big[4 \left(\psi_{i+1,j}^{\nu} + \psi_{i-1,j}^{\nu+1} + \psi_{i,j+1}^{\nu} + \psi_{i,j-1}^{\nu+1} \right) + \psi_{i+1,j+1}^{\nu} + \psi_{i+1,j-1}^{\nu+1} + \psi_{i-1,j+1}^{\nu} + \psi_{i-1,j-1}^{\nu+1} - \frac{6\Delta^2}{m_j^2} \hat{\hat{\zeta}}_{i,j} \Big]$$

$$\text{for} \quad 2 < i < 58 \qquad 2 < j < 44$$

where: ν represents the iteration step

ψ represents the stream function

$\hat{\hat{\zeta}}$ represents smoothed rel. vorticity

C_1 and C_2 represent coefficients including overrelaxation

with the Neumann boundary condition. Thus the initial values of relative vorticity and stream function are prepared for use by the forecast program.

The forecast program begins by calculating the absolute vorticity

$$\eta_{i,j} = \zeta_{i,j} + f_j$$

where: η represents the absolute vorticity

f represents the Coriolis parameter

over the entire grid. After the assumption of vorticity conservation, the finite-difference Jacobian operator is used to obtain an approximation of the horizontal advection of absolute vorticity. Then follows a solution for the change of stream function with time by the iteration formula

$$\left(\frac{\partial\psi}{\partial t}\right)^{\nu+1}_{i,j} = C_3 \left(\frac{\partial\psi}{\partial t}\right)^{\nu}_{i,j} + C_4 \left[\left(\frac{\partial\psi}{\partial t}\right)^{\nu}_{i+1,j} + \left(\frac{\partial\psi}{\partial t}\right)^{\nu+1}_{i-1,j} + \left(\frac{\partial\psi}{\partial t}\right)^{\nu}_{i,j+1} + \left(\frac{\partial\psi}{\partial t}\right)^{\nu+1}_{i,j-1} + \frac{\Delta^2}{m_j^2}\left(\underset{\sim}{V}\cdot\underset{\sim}{\nabla}\eta\right)_{i,j} \right]$$

$$\text{for } 3 < i < 57 \qquad 3 < j < 43$$

where: C_3 and C_4 are coefficients including overrelaxation

$\underset{\sim}{V}$ represents the horizontal velocity of the mean wind

$\underset{\sim}{\nabla}$ represents the horizontal del operator

using the Liebmann sequential relaxation technique, with the outer 2 rows held constant. After the first step, normally 4-9 iterations are required for the solution of each succeeding time step. Convergence is accepted when an absolute value change of less than 1 m^2 sec^{-2} is obtained:

$$\left| \left(\frac{\partial\psi}{\partial t}\right)^{\nu+1}_{i,j} - \left(\frac{\partial\psi}{\partial t}\right)^{\nu}_{i,j} \right| < 1 \; m^2 sec^{-2} \quad \text{for} \begin{cases} 3 < i < 57 \\ 3 < j < 43 \end{cases}.$$

Then using a centered time step (except on the first step, of course) the succeeding value of the stream function is computed:

$$\psi_{i,j,k+1} = \psi_{i,j,k} + 2\,\Delta t\left(\frac{\partial\psi}{\partial t}_{i,j,k}\right).$$

where: k represents the number of the time stop

Δt represents the time increment (30 min.)

Thereafter, the successive values of absolute vorticity are computed by the finite-difference formula:

$$\eta_{i,j} = \frac{m_j^2}{\Delta^2}\left(\psi_{i+1,j} + \psi_{i-1,j} + \psi_{i,j+1} + \psi_{i,j-1} - 4\psi_{i,j}\right) + f_j\ .$$

[Readers desiring a reference text for applications of finite difference techniques to meteorology are referred to the recent publication by Haltiner (1971).]

At the end of time steps 24, 48, 72, 96, 120 and 144 (i.e., each twelve hours), a smoothing subroutine is applied to the field of stream function -- and a smoothing of the vorticity field is thereby indirectly accomplished.

The tropical storm is identified at each printout time by reference to the associated stream function minimum and vorticity maximum. As the two drift apart during the forecast, due to the effects of truncation error, the convention has been established to position the storm halfway between them. At times, the minimum in the stream function disappears during the course of the forecast -- occurring often when the storm is weak or superimposed on an ever-stronger basic current. In this event, the position of the storm is presumed to be indicated by the vorticity maximum alone.

ATLANTIC HURRICANES AND TROPICAL STORMS (Sept. 8-13, 1971)

The period September 8-13, 1971 presented a most profitable opportunity for application of the SANBAR model. Not only were storms located in the Caribbean Sea, Gulf of Mexico, and the western Atlantic, but never were there fewer than two named storms. Hurricane Nanette located off Baja California in the Pacific Ocean was included in the analysis from 0000Z September 8th through 1200Z September 9th to add to the realism of the mean flow pattern.

In preparation for studying the forecasts, it should be noted that the tracks plotted for the actual storms are those published after-the-fact by NHC (Simpson and Hope, 1972). However, the forecasts start from the real-time operational positions. Differences in the actual track positions and forecast initial positions often are further increased by the mid-point between the vorticity maximum and the stream function minimum being removed from the operational position at time zero.

Resisting temptation -- and thus saving the best for last -- I will present the storms in chronological order.

EDITH

In the forecasts for Edith (Figure 3) the first two forecasts have creditable accuracy for landfall near the Honduras/Nicaragua border, but curvature toward the north is not hinted until the 090000Z forecast. (Table 2 gives the relevant storm parameters used for Edith's forecasts.)

Table 2. Storm Parameters for Hurricane Edith (Eye diameter = 20 nm. throughout)

Forecast time	Max. sfc. wind (knots)	Influence radius(nm)
080000Z	61	350
081200Z	66	300
090000Z	92	350
091200Z	132	350
100000Z	122	200*
101200Z	66	350
110000Z	70	400
111200Z	52	325
120000Z	35	300*
121200Z	35	300*
130000Z	35	300

* indicates re-run

By the 091200Z forecast, Edith was embedded in a northwestward mean current, on the western periphery of the subtropical ridge extending westward over the Caribbean. The direction of the forecast was excellent, but the forecast speed was slow as we will come to expect.

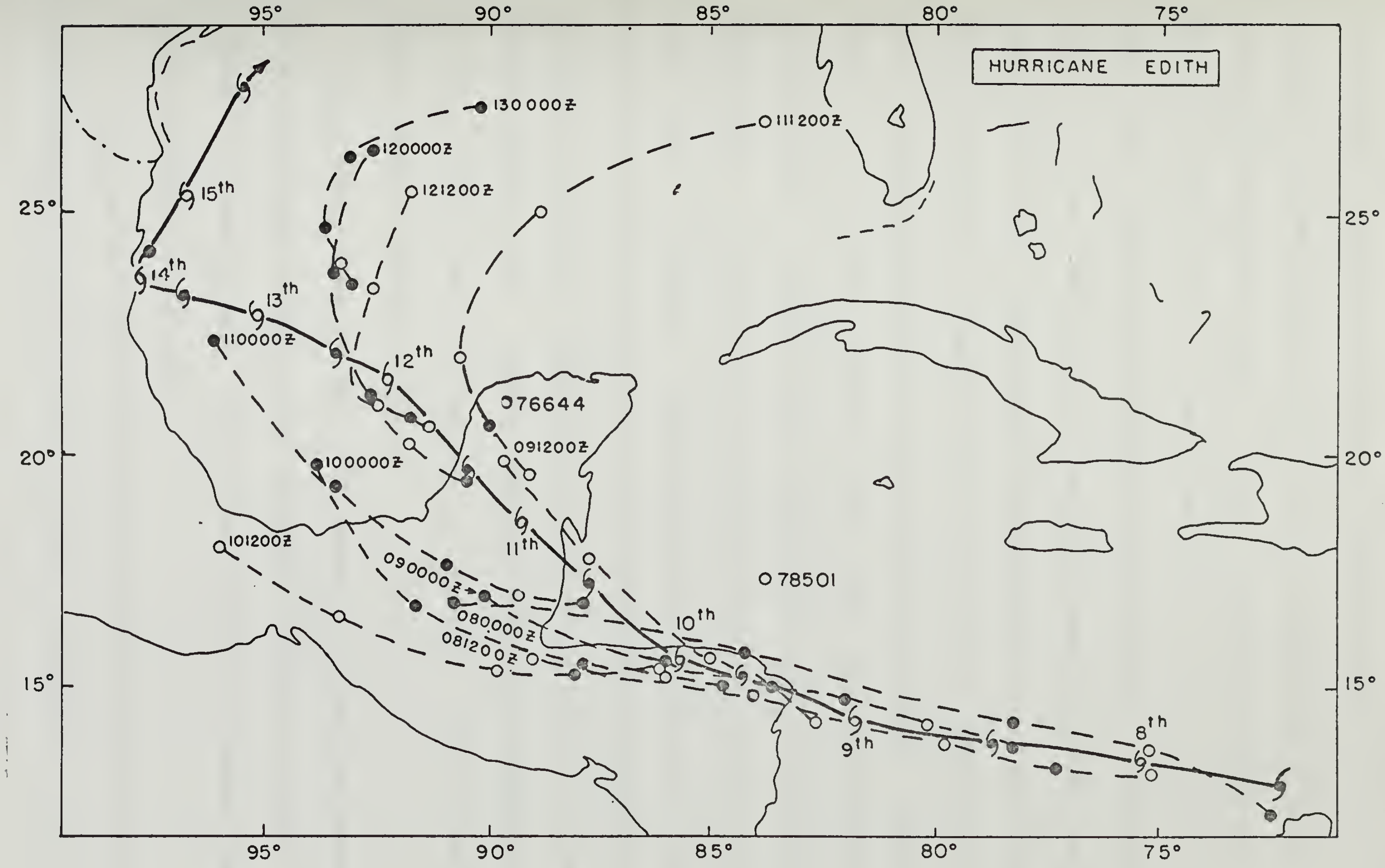

Fig. 3. Observed best track for hurricane Edith 1971 (solid line) from 0000Z 8 September to 0000Z 16 September. Twelve-hourly positions are shown by solid or open hurricane symbols, the latter indicating the 1200Z position on the dates shown adjacent to them. The 72-hr forecast tracks appear as dashed lines, with 12, 24, 48, and 72-hr forecast positions indicated similarly by solid or open circles. The number at the end of each forecast track represents the initial time of the prediction.

The 100000Z forecast as shown is a re-run. The original forecast is not shown, because any operator, having noticed that its 12-hour forecast reversed Edith's course into the strong easterlies, could have taken corrective action. In fact, an overly zealous hurricane influence radius (400 nautical miles) had been used as a storm parameter on the original operational analysis program. Since Edith was at the time a dangerously strong hurricane (122 knots maximum surface wind), the subtracting of the model hurricane wind from the mean wind reported at Swan Island, station 78501, (097°/27.6 knots) left a strong westerly wind at the station, (294/15.9). Accordingly, a quick re-run of the analysis program using a 200 nm. radius for the hurricane -- thereby greatly reducing the model storm wind at Swan Island -- provided a new recalculated (storm purged) wind at Swan Island of 090/13.1. Therefore, the many grid-points nearby which use the Swan Island wind in their regression equations were given more believable easterly winds before the addition of the model hurricane wind. (Again, although the forecast speed was slow, the 72-hour error was only 140 nm. -- comparable with the best state-of-the-art 24-hour error.)

The 101200Z forecast was poor, caused by a building westward of the subtropical ridge by the barotropic forecast; however, the 110000Z recovered to have only a 60 nm. error at 72 hours, despite its poor initial direction.

Commencing at 111200Z the deterioration of SANBAR's accuracy in forecasting for Edith becomes obvious. Although the first 12-hour

forecast is quite good, thereafter Edith is taken erroneously northeastward around the subtropical high.

The presence of tropical storm Fern (to be discussed next), going inland over Corpus Christi, Texas, may have been instrumental in this forecast. At the initial time the two storms were only 660 nm. apart. Studying a sample of northern Pacific storms over water, Brand (1970) found that storms having separation distances of less than 750 nm. were subject to an obvious "Fujiwhara effect". Although both storms had a maximum surface wind of 52 knots, the maximum grid-point value of absolute vorticity of Fern, 216 x 10^{-6} sec^{-1} was much stronger cyclonically than that of Edith, 167 x 10^{-6} sec^{-1} -- Edith being embedded in the western periphery of the subtropical high as noted earlier. In fact, whereas Edith had become the dominant vortex of the two before 130000Z (Fern had weakened to a tropical depression by 120400Z), the barotropic prognosis maintained Fern as the stronger. Thus with Fern stronger in the forecast, the interaction would have been onesided causing Edith to move northward where it was engulfed sooner by the strong westerlies. Additionally, the mutual attraction consistent with atmospheric systems, but excluded from theoretical nondivergent systems (Brand, 1970), could have been instrumental in the northwestward track of the real Edith.

The 120000Z forecast represents a re-run. An initial movement of the forecast toward the southwest prompted a check of the analysis winds nearby. It was immediately obvious that although Edith had weakened to a 35-knot wind maximum, purging of the storm wind at

Merida, Mexico, station 76644 (only 73 nm. distant) had left a northwesterly recalculated wind (335/9.4) at Merida. Therefore, grid points nearby naturally responded with northwesterly winds. This difficulty was removed by substituting for station 76644 a wind which (when purged of the model hurricane wind) would leave a flow equal to the most recent operational estimate of the storm's course and speed. Thus replacing the original station 76644 wind 108/10.8 with 125/26 yielded a recalculated wind of 113/7.7 (close to the past 12-hour movement vector of Edith). The forecast using this correction provided a respectable prognosis for only 24 hours after which the relative closeness of an overly strong Fern to the west and the subtropical high to the east appeared again to dominate as at 111200Z.

Forecasts at 121200Z and 130000Z unfortunately represent the same effect, despite efforts to improve the 121200Z forecast. Since by this time Fern had weakened to a depression, no storm parameters were entered on the original run for that storm. Accordingly, it was theorized that since no storm purging would be effected upon the yet strong mean winds surrounding the vortex in southern Texas, the wind analysis for grid points in the western Gulf would be inaccurately portrayed. However even with storm parameters entered for Fern, little improvement was realized.

Repositioning the 130000Z forecast to begin at the actual track position, one finds that the 72-hour error of 280 nm. is not excessive for a sharply recurving hurricane.

FERN

Figure 4 displays the path of Fern after it has moved southward out over the Gulf. Also included are the SANBAR forecasts with storm parameters displayed in Table 3. In view of the meandering path of Fern, the three first forecasts are not poor ones, and the 090000Z forecast comes within 30 miles of the point of landfall despite the 90-degree direction error.

Table 3. Storm parameters for Fern (Eye diameter = 20 nm. throughout)

Forecast time	Max. sfc. wind (knots)	Influence radius (nm.)
080000Z	44	275
081200Z	48	325
090000Z	62	325
091200Z	79	375
100000Z	66	375
101200Z	66	350
110000Z	52	325
111200Z	52	300

The error of a northward forecast from 091200Z is quickly explained when one examines the recalculated winds of the surrounding stations. Station 72240 with an input wind of 140/22.5 had a recalculated wind of 199/11.7. Likewise, station 72255 went from 039/11.6 to 208/9.9, and station 72250 (missing) had a wind of 227/15.4 computed from its regression equation. These three stations naturally

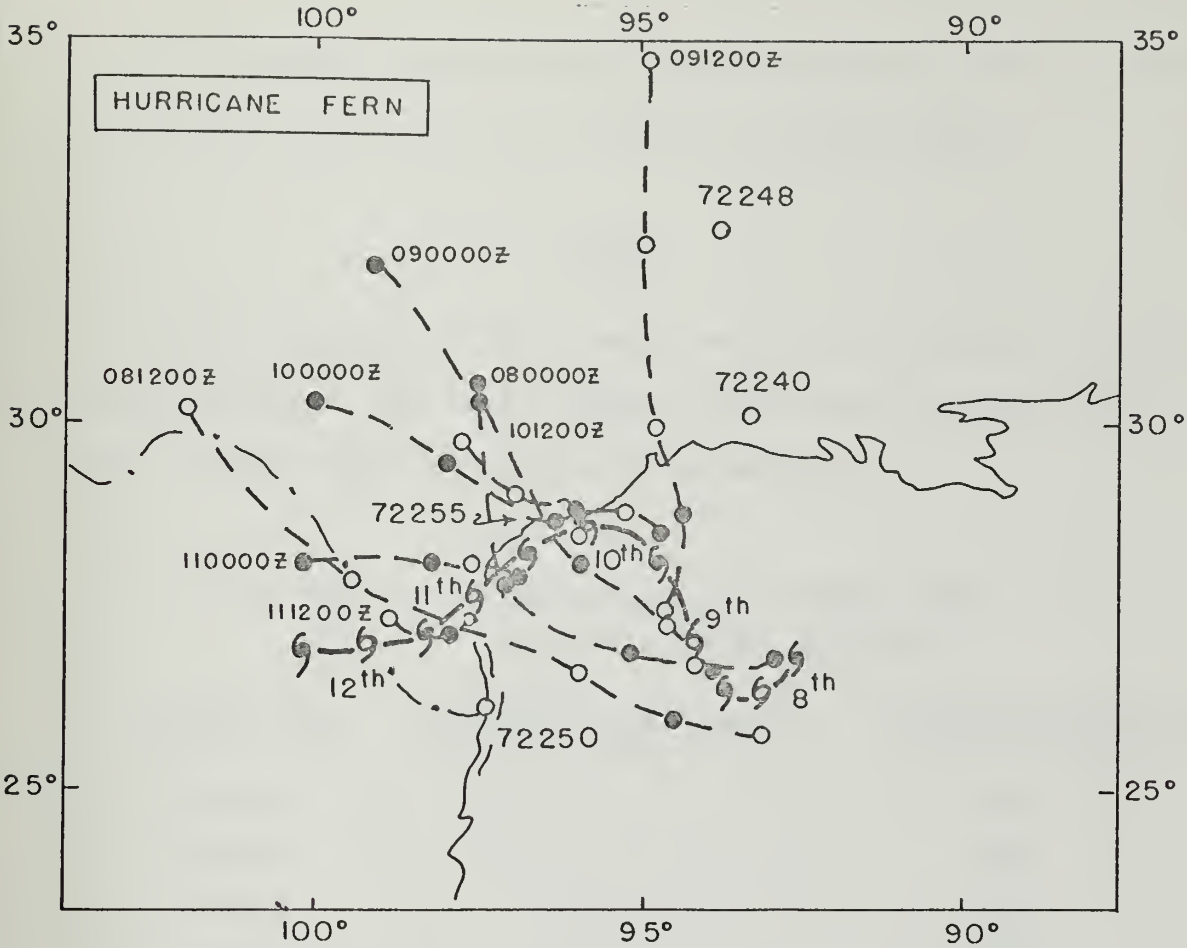

Fig. 4 -- Hurricane Fern from 0000Z 8 September to 0000Z 13 September. For details see Fig. 3. (Forecasts beginning 101200Z do not extend to 72 hours.)

supplied a strong southerly component to their surrounding grid-points.

The forecast from 100000Z was quite good in predicting the point of landfall, but again at 101200Z an immediate northwestward movement was predicted. The movement, though not completely understood, could have been influenced by both stations 72248 and 72255 having recalculated winds from 127°.

The shortened forecasts from 110000Z and 111200Z returned to more acceptable errors, but by this time Fern was moving inland.

GINGER

Figure 5 represents only a small portion of the record lifetime of Hurricane Ginger. As before SANBAR forecasts have been added with Table 4 listing the applicable storm parameters.

Table 4. Storm parameters for Ginger (Eye diameter = 20 nm. throughout)

Forecast time	Max. sfc. wind (knots)	Influence radius (nm.)
110000Z	55	325
111200Z	61	350
120000Z	70	375
121200Z	70	350*
130000Z	80	350*

* indicates re-run

The first three forecasts show the typical slow bias, but the 120000Z 72-hour error is held to 180 nm. when Ginger commences slowing and curving toward the south.

The 121200Z forecast was a rerun for obvious reasons. Due to the proximity of bogus point 9 (30°N, 60°W) to the hurricane center at the time of analysis, 12 nm., the input wind for that bogus point (270/33.0) reduced to a recalculated wind of 068/17.0. Accordingly a substitute

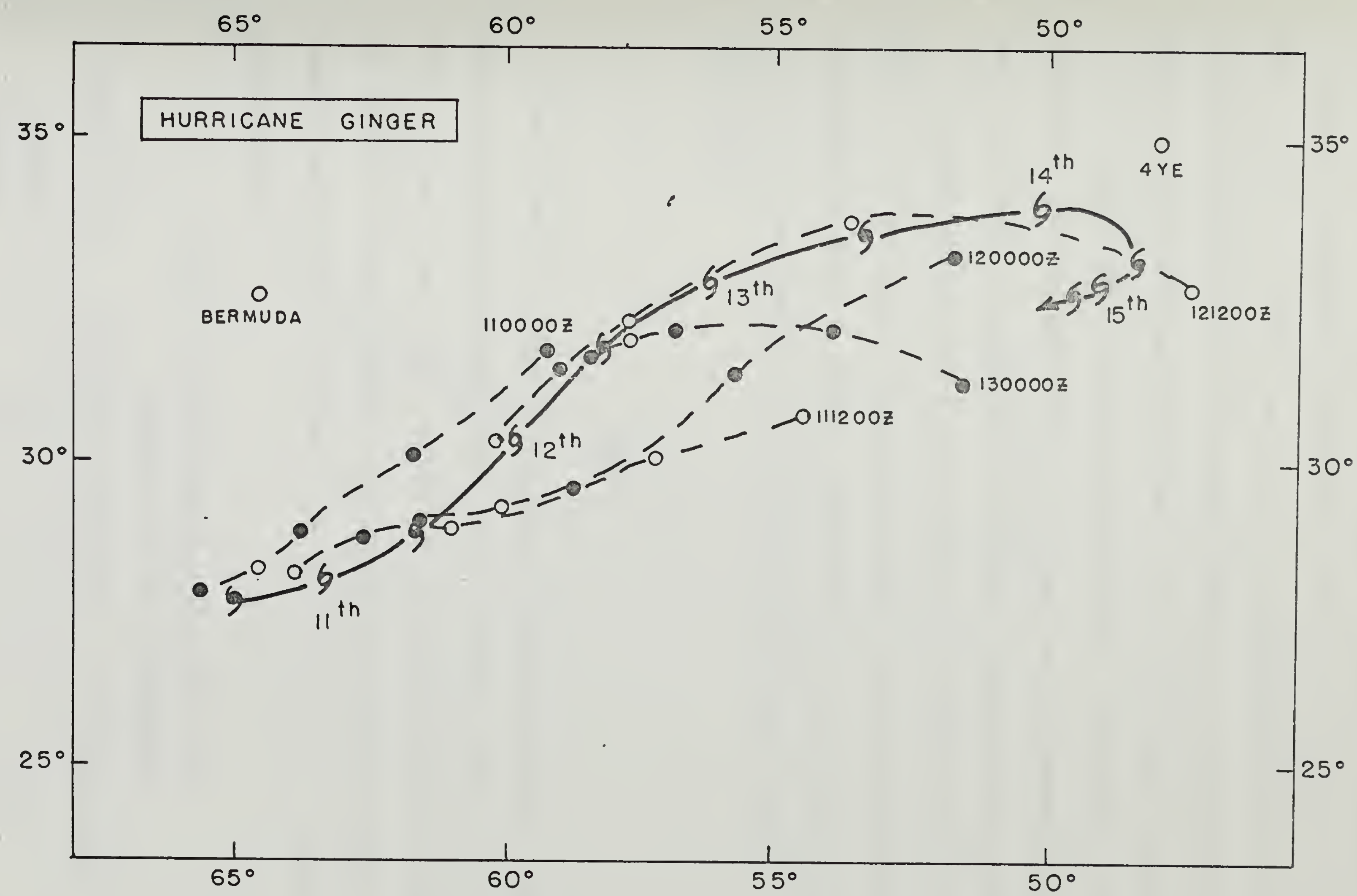

Fig. 5 -- Hurricane Ginger from 0000Z 11 September to 0000Z 16 September. For details see Fig. 3.

wind for bogus point 9 was quickly prepared from the hurricane's immediate past movement vector plus the model hurricane wind vector. This new wind of 257/58.0 resulted in a recalculated wind of 230/10.8 closely approximating the hurricane's movement vector as would have been known by the operational forecaster. Full credit cannot be accepted for the small 72-hour forecast error of 85 nm. Not only did a reverse of the hurricane's course reduce the error, but the SANBAR forecast was forced toward the southeast by boundary limitations (not shown).

The same re-run technique was used on the 130000Z forecast for Ginger. The substantial reduction in speed of this forecast can be attributed, at least in part, to the weakening of the westerly components at Ocean Station E as well as at bogus points 9 and 10 (30°N, 50°W).

HEIDI

The forecasts of SANBAR on tropical storm Heidi (Figure 6 and Table 5) are presented mostly as a thing of beauty, noting that the 48-hour forecast error from 130000Z was less than 80 nautical miles. The forecast certainly supports the statement by Sanders (1970), " . . . dramatic acceleration of storms in the westerlies can be accounted for barotropically.".

Table 5. Storm parameters for Heidi (Eye diameter = 20 nm. throughout)

Forecast time	Max. sfc. wind (knots)	Influence radius (nm.)
121200Z	40	300
130000Z	45	300

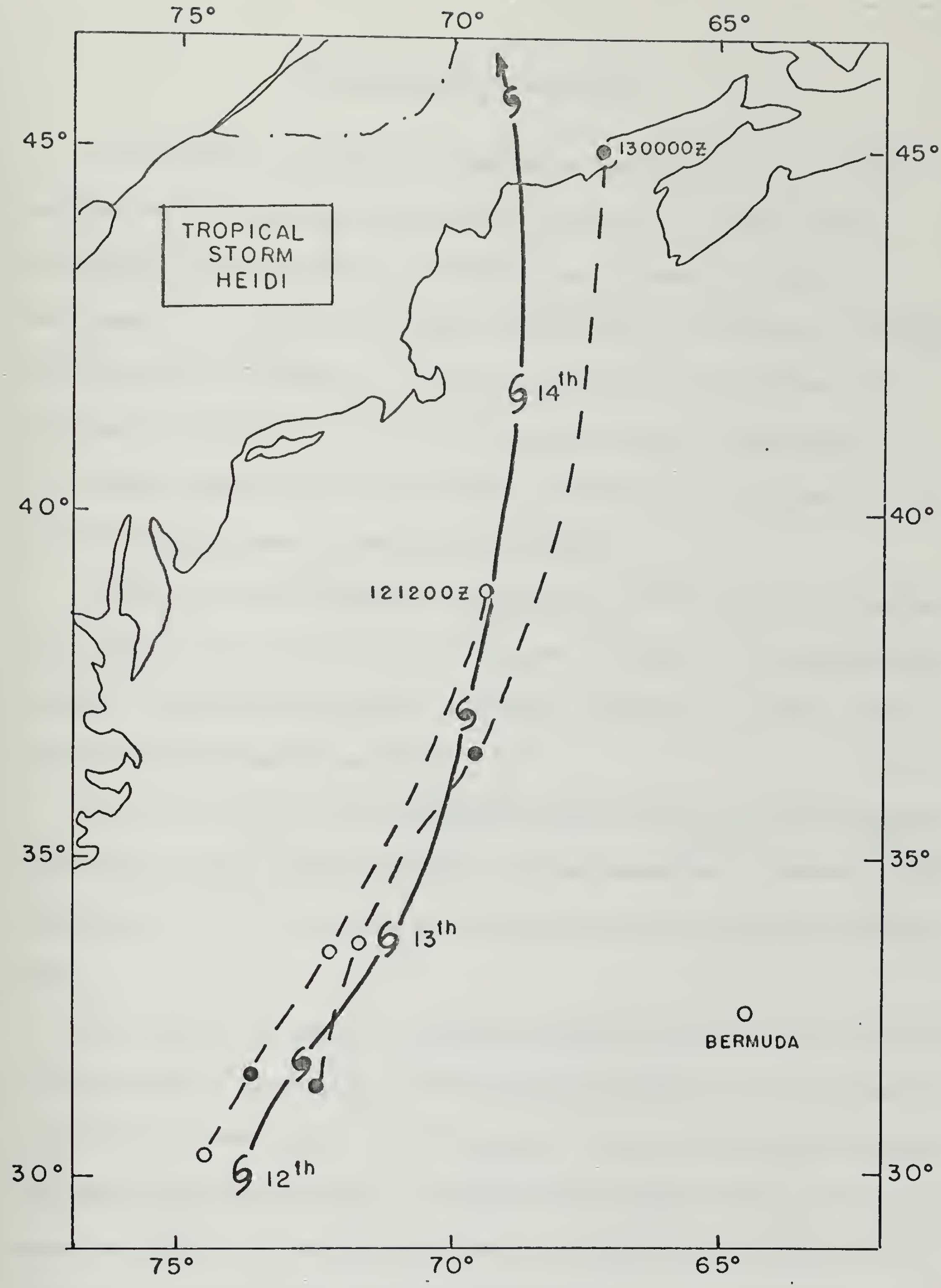

Fig. 6 -- Tropical storm Heidi from 1200Z 12 September to 0000Z 15 September. For details see Fig. 3. (Forecasts extend only to 48 hours.)

DISCUSSION AND CONCLUSIONS

In reviewing the results of SANBAR as applied in the previous section, it is found that erroneous calculations of storm purged winds led to poor forecasts at least twice for each of the three hurricanes. The other more nebulous difficulty arose when two storms came into close proximity. During the infrequent occurrences of this latter difficulty, it is felt that operational forecasters must study stream function and vorticity patterns, and formulate subjective modifications to the forecast tracks.

As for the more prevalent difficulty of calculating storm purged winds, two types of corrective action are available. The model storm wind may be modified by varying its input parameters, or the input (observed) winds may be modified.

During this study, the alteration of the storm's maximum influence radius (Edith 100000Z) proved to be advantageous. Naturally, the application of this technique may be germane during operational situations.

The several instances of modifying the input wind observations near the storm center proved to be very effective during this investigation. The author is encouraged to have learned through privileged communication that NHC will institute a program modification during the hurricane season of 1972 which should practically eliminate the problem of the recalculated wind. This modified SANBAR model, as written by Dr. Arthur Pike of NHC, requires that the analyzed wind at all stations

within the influence radius be represented by the sum of the symmetric storm circulation vector and the storm movement vector.

In short, the modified SANBAR effects automatically those changes which the author undertook at single stations on only a few forecasts. More importantly, the modified SANBAR will apply these corrections for every forecast and for all stations within the influence radius. Comparison of SANBAR forecasts of this study with those of the modified SANBAR are displayed in Tables 6 and 7.

Table 6. Forecast Error Averages (nm.) for Edith and Fern (080000Z, 101200Z, 110000Z)

	12-hr	24-hr	48-hr	72-hr
SANBAR (M.I.T.)	60(6)	96(6)	143(6)	161(4)
SANBAR (modified)	39(6)	63(6)	95(6)	160(4)

(Numbers in parenthesis indicate the number of forecasts compared. All forecasts were repositioned so that their initial positions agree with that of the after-the-fact track.)

Table 7. Forecast Error Averages (nm.) for Ginger and Heidi (121200Z and 130000Z)

	12-hr	24-hr	48-hr	72-hr
SANBAR (M.I.T.)	44(4)	80(4)	171(4)	95(2)
SANBAR (Modified)	29(4)	59(4)	188(4)	272(2)

(Numbers in parenthesis indicate the number of forecasts compared. All forecasts were repositioned so that their initial positions agree with that of the after-the-fact track.)

In defense of this small and selective sample, it must be stated that results for the modified SANBAR were available only for the 5 times displayed. Recognizing that the sample size is inadequate as well as that input storm parameters and bogus winds differed for the two forecast systems, only during Ginger and Heidi did the original SANBAR have smaller errors than did the modified SANBAR. In particular during both original SANBAR forecasts for Ginger, corrections were made for recalculated winds. Indirectly, too, this may indicate the worth of using satellite film strips in preparing oceanic bogus data, for it is here that the original SANBAR did better at 48 and 72 hours.

In regard to the slow bias of SANBAR which has become well known to the operational forecasters, subjective modification must be attempted awaiting such time as an objective improvement can be offered. A suspected equivalent barotropic effect (NHC, 1972) which tentatively suggests multiplying the individual winds by about 1.3 has not been successful to date.

In addition to a possible new baroclinic model (NHC, 1971), improvements to the statistical and analog methods as well as those to SANBAR should foretell of a more promising future for the hurricane track forecaster.

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